

RECENT RESULTS IN THE STUDY OF PROBLEMS OF MIXING AND REATTACHMENT

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RECENT RESULTS IN THE STUDY OF PROBLEMS OF MIXING AND REATTACHMENT

Pierre Carrière and Maurice Sirieix

ABSTRACT

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Experiments on conical separation carried out in the almost complete absence of perturbation have confirmed that the Chapman-Korst criterion of turbulent separation must be modified. Work carried out in plane flow and flow of revolution, in the presence of an initially turbulent boundary layer of negligible thickness, leads to the same conclusion. It is not yet possible to exactly construct a criterion of separation encompassing all the results obtained, but an approximate approach is proposed that differs greatly from that of Chapman-Korst.

Introduction

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Analysis of two-dimensional flow behind an abrupt breakoff of the wall has substantially contributed to the elucidation of reattachment problems.

The generally adopted model of flow is that of Korst and Chapman (fig. 1). It consists in distinguishing an isobaric mixing layer followed by a reattachment zone from the dead water and the external flow (M_1). In this reattach-

ment zone, the external flow is subjected to recompression due to deviation ψ which the downstream wall imposes on it. It is first assumed that the reattachment phenomenon is determined by a condition of compatibility between the final pressure p_2 acquired by the external flow after reattachment and the generating

pressure $(p_i)_1$ available at the start C of the reattachment zone on the stream

line (1) which ends at the stopping point R on the wall. The Chapman-Korst escape criterion consists in writing $p_2 = (p_i)_1$. The application of this

criterion to a given (M_1) is thus reduced to a study of the development of the

*Numbers given in margin indicate pagination in original foreign text.

zone of mixing in order to obtain the pressure p_i on each stream line so as to determine the boundary line (1) by comparison with p_2 .

A solution to this problem has been proposed by Korst for the general case of a preexisting turbulent boundary layer at the point of separation. The properties of the flow to any abscissa x of the zone of mixing can thus be expressed as functions of a parameter characterizing the position of each stream line, for example, the flow q between the stream line considered and the stream line (j) originating from the point of separation. The line (j) separates the fluid coming from upstream and the fluid coming from the dead water. In the absence of suction or blowoff in the dead water, the criterion then amounts to the determination of the flow (M_1) by trial and error, such

that $q = 0$, i.e., $(p_i)_j = p_2$.

On the basis of these studies we have tried to express the escape criterion so as to be able to readily separate, in the applications, the influence of the various parameters which may be involved in the phenomenon.

We have shown (ref. 2) that this criterion may be written in the form of a relation

$$\psi = \psi (M_1, C_q) \quad (1)$$

giving the deviation ψ which the flow undergoes in the reattachment zone as a function of M_1 and of a generalized flow parameter C_q assumed to be small and

defined in plane flow by

$$C_q = \frac{q}{\rho_1 u_1 L} \left(1 - \frac{v}{u_1} \right) + \frac{\delta^{**}}{L} \quad (2)$$

where q = mass flow which may be injected into the dead water,
 v = longitudinal component of the injection velocity,
 L = length of the separated zone,
 u_1 = velocity in (M_1),

δ^{**} = thickness of the displacement of the boundary layer at the origin of the isobaric mixing.

The case $C_q = 0$ corresponds to an unperturbed ideal case.

If C_q is small enough, the function $\psi (M_1, C_q)$ can be determined from a study of the ideal case perturbed only by a blowoff effect at negligible speed ($v = 0$, $\delta^{**} = 0$), and we can write in the linearized form

$$\psi = \bar{\psi}(M_1) + C_q \cdot \bar{\psi}'(M_1). \quad (3)$$

Functions $\bar{\psi}(M_1)$ and $\bar{\psi}'(M_1) = \partial\psi/\partial C_q$ are obtained without difficulty if the Chapman-Korst criterion is adopted.

The validity of this criterion has been proven many times in turbulent flow by general wind tunnel experiments behind an abrupt breakoff of the wall. Generally, however, the interpretation did not consider the initial boundary layer. We nevertheless see from expression (2) that this effect is equivalent to a blowoff effect, and this phenomenon is known to be extremely sensitive to this factor. Thus, the proposed verifications were not significant. /4

In our preceding communication at the Stresa Congress on Applied Mechanics, we used the summarized theoretical analysis and experiments where the initial boundary layer had been carefully measured to demonstrate for the first time that the Chapman-Korst escape criterion led to contradictions and had to be reexamined.

Returning to the same arguments, Nash (ref. 3) has proposed a corrected expression of the criterion in the form

$$\frac{P_{i1} - P_1}{P_2 - P_1} = N$$

expressing the fact that the flow on (1) in the reattachment zone is isentropic up to stopping point R, but that the pressure of this point is only a fraction N of the total pressure jump. N must be determined experimentally.

Unfortunately, there have not yet been enough fundamental experiments in supersonics conducted under sufficient purity conditions to permit us to obtain a form of $\bar{\psi}(M_1, C_q)$ that would be acceptable for the applications.

We therefore considered it necessary to continue research with the aim of filling this gap.

This report concerns the first results obtained from this research.

1. Study of Conical Reattachment /5

1.1 Definition of Model

An attempt was made first to define experimental conditions permitting study of the free turbulent reattachment of a two-dimensional supersonic flow in the absence of any extraneous influence. The flow chosen was axisymmetric, so as to remove boundary layer effects that are difficult to evaluate and that appear in the classical setups in plane flow. In addition, the following conditions were combined:

- (1) Upstream boundary layers of negligible thickness,
- (2) Rectilinear separation boundaries,
- (3) Constant direction of the wall at reattachment,
- (4) Thermal equilibrium.

The arrangement in figure 2 satisfies these requirements.

The scale model consists of a cone of angle 2θ , extended along its axis by a very small conical tip ($2\theta_s$) with variable distance of emergence OO' .

This scale model is placed without incidence in a uniform flow (M_0, p_{i0}, T_{i0}).

When θ exceeds a certain value θ_0 , for constant OO' the flow separates at SS' , where the thickness of the boundary layer is negligible, and becomes re-attached on cone 2θ .

When angle θ_s is suitably adjusted, the flow obtained is very close to conical up to the reattachment.

This arrangement was tested at values of M_0 between 3 and 6 in wind tunnels R_1 and R_2 at Chalais-Meudon. It was possible to cause considerable variation in the generating pressure and hence in the unit Reynolds number ($1.5 \cdot 10^4 \leq (R_e)_{0/cm} \leq 2 \cdot 10^6$).

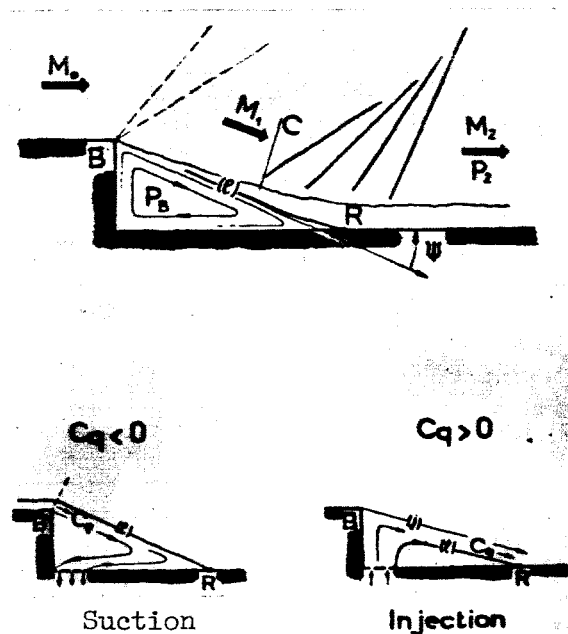


Figure 1. Chapman-Korst flow model.

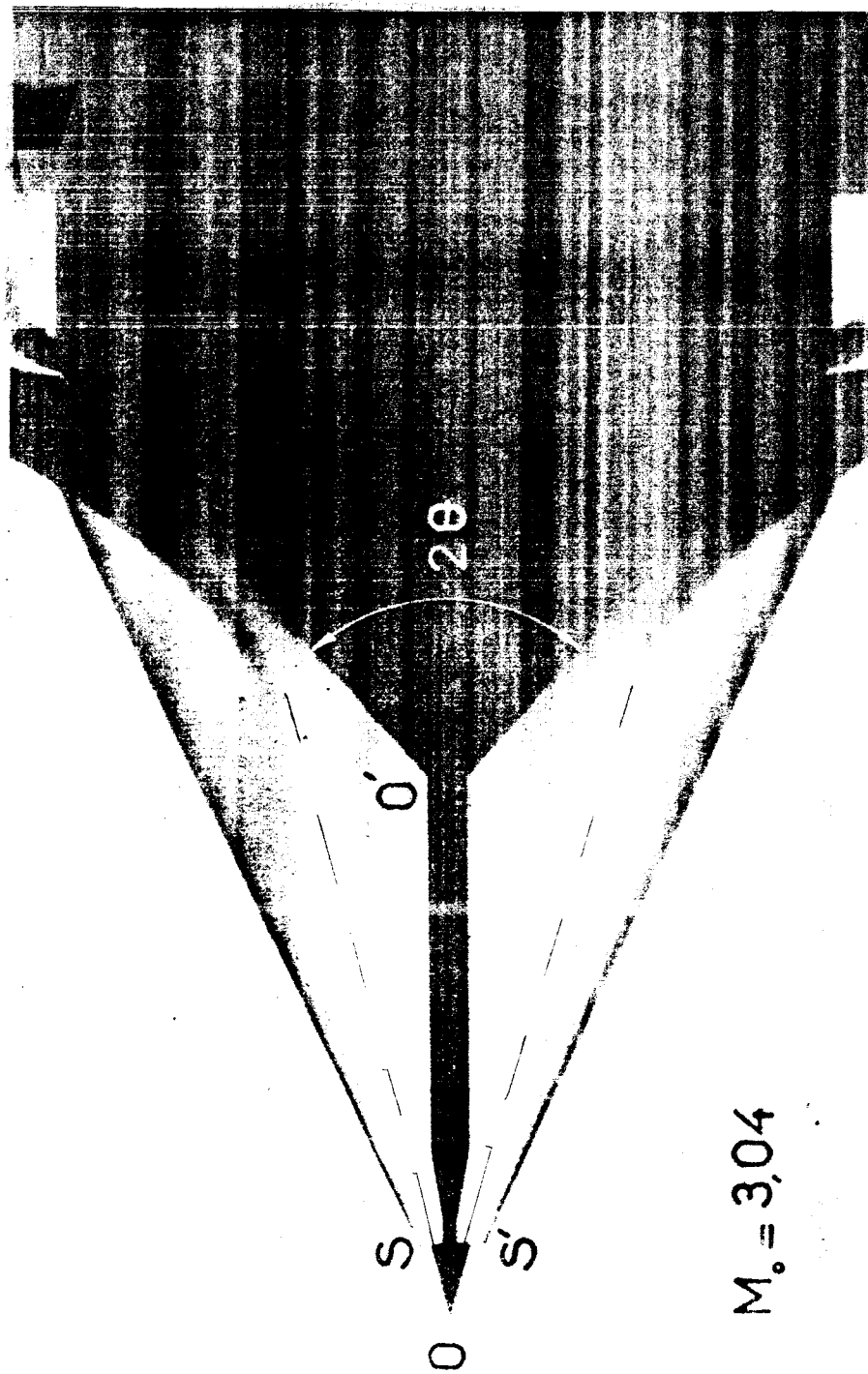


Figure 2. Conical separation.

In addition to schlieren analysis of the flow, pressures were measured ^{/6} by wall taps arranged at the base of the cone $2\theta_s$ and on a generatrix of the obstacle cone 2θ .

The variations of M_1 , the only significant parameter of the problem, are obtained for a Mach M_0 given by modifying the couple (θ, θ_s) . The flows thus obtained are perfectly stable. The study was limited to the case where the flow is entirely supersonic all the way to the downstream of the reattachment. Under these conditions, M_1 varied from 2.3 to 4.

1.2 Preliminary Study of the Perturbation Factors

1.2.1 Influence of the Reynolds number: Definition of testing conditions

Preliminary tests permitted verifying that for flows which we shall call conical separations there exist reattachment conditions which are practically independent of the Reynolds number when the reattachment boundary is completely turbulent. In these tests, for fixed geometrical configuration of the scale model and M_0 , we find that when the unit Reynolds number increases from a relatively small value ($Re_0 \simeq 1.5 \cdot 10^4/\text{cm}$, for example), the ratio p_B/p_{i0} decreases rapidly at first, passes through a minimum value, then increases again and tends toward an approximately constant value, at least in the range studied ($Re_0 \leq 2 \cdot 10^6/\text{cm}$).

Such an evolution was demonstrated repeatedly in studies devoted to the base pressure and in various proposed explanations (ref. 3). However, to our knowledge none of them places sufficient emphasis on the close correlation existing in the presence of a negligible initial boundary layer between the evolution of the base pressure and the position of the transition.

When the latter is located on the boundary of the separation, its abscissa L_T relative to the origin of the separation is marked either by the presence of a perturbation wave which is distinctly visible on the schlieren photograph (fig. 3), or by a change in the characteristic appearance of the boundary ^{/7} of the separation.

The curve showing the evolution of p_B/p_{i0} as a function of L_T/L , L being the theoretical length of the separation (fig. 4), shows in a very characteristic fashion, on the one hand, that the minimum of the base pressures is obtained when the transition is located at the end of the isobaric mixing zone, and on the other hand, that the limiting value is practically attained even before this zone of mixing is completely turbulent ($L_T/L \simeq 0.2$).

Figure 5 shows the same phenomena in the more familiar pressure-Reynolds diagram. When the mixing layer becomes progressively turbulent, its relative thickness increases, causing the reattachment zone to expand (fig. 6). In the case studied, the effective length L_M/L of the quasi-isobaric region is of the order of 0.8 in a completely turbulent regime, but close to unity in a laminar regime.

$M_o = 3.04$



Perturbation due
to transition

Figure 3. Transition in mixing zone.

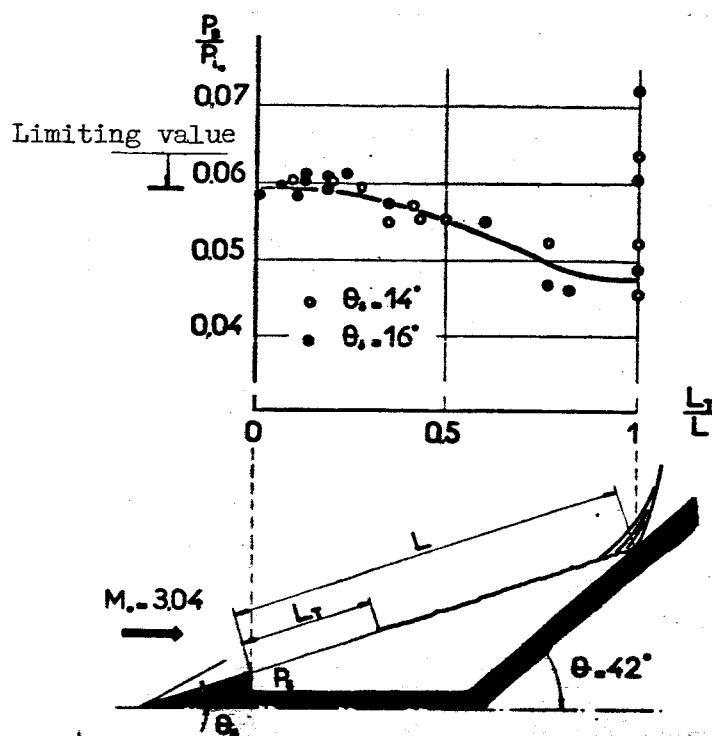


Figure 4. Relation between separation pressure and transition.

The following results pertain only to the limiting turbulent case.

1.2.2 Residual curvature factors: Effect of matching the tip

Flow along the separation boundary can be rigorously conical only if it extends the conical flow exactly at the forward tip.

If angle θ_s is not rigorously matched with this condition, a perturbation appears at the origin of the separation whose repercussions on the downstream flow are in principle capable of modifying the reattachment conditions (curve of the jet line).

To verify the matching tolerance, we studied the effect of greatly mismatched tips.

Results show (fig. 7) that perturbations corresponding to variations of $\pm 2^\circ$ around the matching angle with unchanged base pressure have practically no effect on reattachment. This tolerance was adopted in subsequent tests.

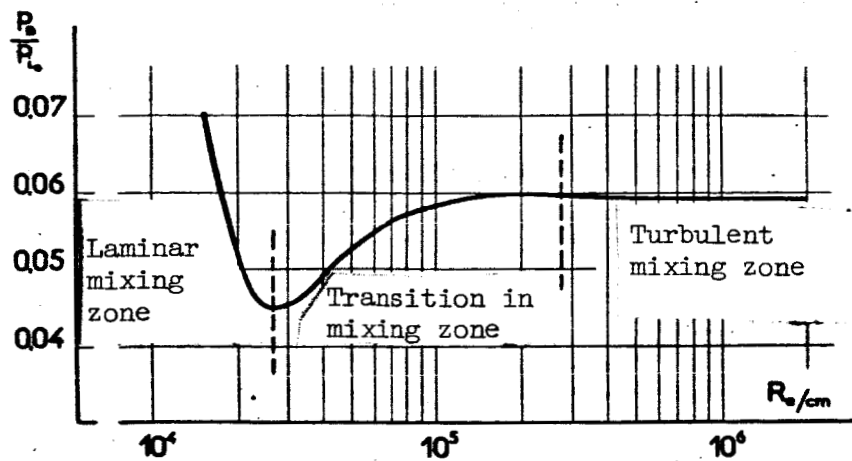


Figure 5. Variation of base pressure with Reynolds number.

1.2.3 Effect of the initial boundary layer

The characteristic parameter of this effect is, in the case of a flow of revolution,

$$C_q = \frac{\delta^{**}}{L} \cdot \frac{r}{R}.$$

In this expression, L represents the mixing length and r/R is the ratio of distances to the axis at separation and reattachment.

For a given configuration, when C_q is small and varies slightly, the correlative evolution dp_B/p_B is a linear function (3) of C_q .

This law was verified by varying the distance of emergence of the tip over a wide range, other conditions being equal.

Under these conditions, δ^{**}/L_0 is constant, and the characteristic parameter is simply the geometrical parameter

$$\frac{L_0}{L} \cdot \frac{r}{R}.$$

Results (fig. 8) confirm the anticipated linear evolution and show that in the majority of cases it was possible to choose a sufficiently large emergence distance, so that the initial boundary layer effect is completely negligible.

However, when this is not the case ($\theta = 36^\circ$, for example), the linearity of the phenomena readily permits extrapolation of the experimental results so that the limiting value of p_B/p_{i0} is obtained.

However, the theoretical slopes are much lower than those given by the 9 experiment. This is because at very high unit Reynolds numbers (true of these tests) when the tip is small, its surface can no longer be considered aerodynamically smooth, and the classical calculation of δ^{**} leads to a value below the actual value.

In conclusion, these experiments lead to the law of conical reattachment corresponding to the case of an initial turbulent boundary layer of negligible thickness.

1.3 Study of the Separated Zone and of the Reattachment Conditions

1.3.1 Conicity of the boundaries

This property appears upon a schlieren examination of the flow. Indeed, when the tip is appropriately matched, the initial shock wave is not altered by any other perturbation, and its direction should therefore be perfectly

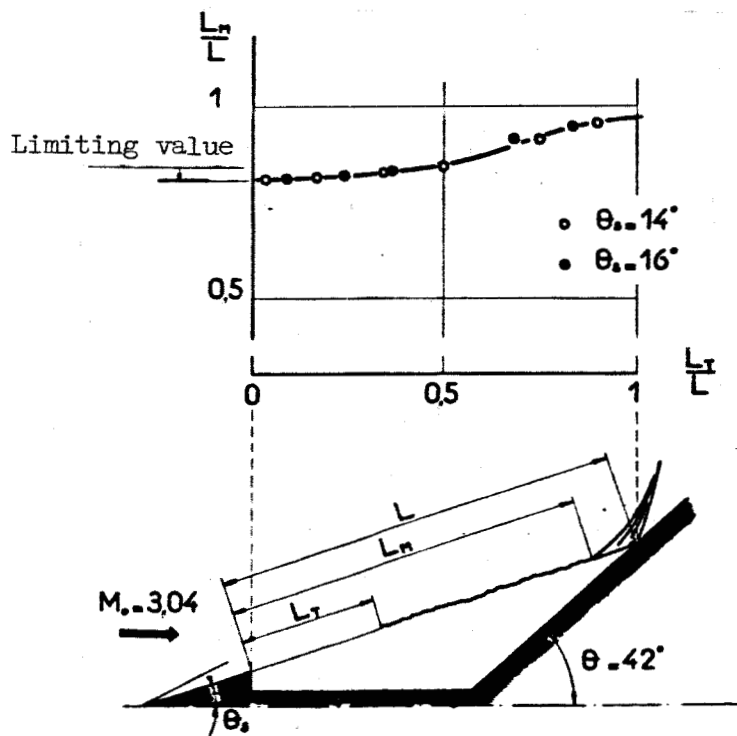


Figure 6. Relative extent of isobaric mixing zone.

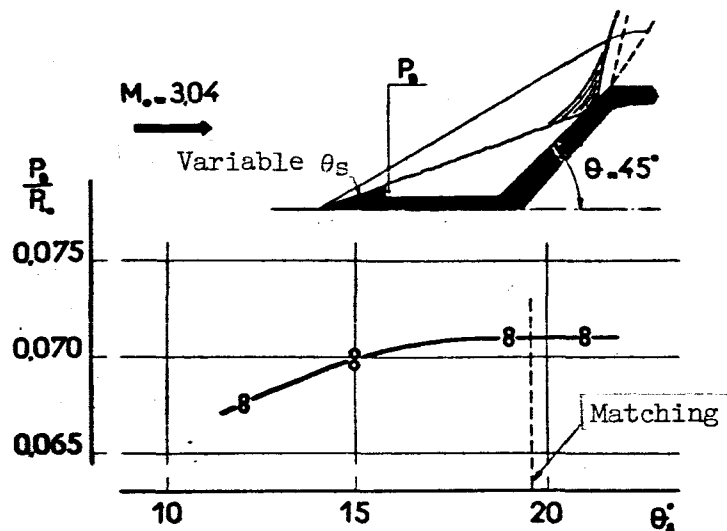


Figure 7. Matching of tip; totally turbulent case.

rectilinear. Its precise fixation was achieved by densitometric probing of the schlieren photographs; the inclination on the axis is practically constant over the entire useful length (fig. 9).

In addition, it was found that the pressure measured at the base of the upstream cone is very close to that which is deduced from the conical sharp angle, as shown in a specific case by figure 10.

It is thus possible to ascertain elimination of curvature factors generally involved in the flows of revolution and which create a difficulty in the interpretation of the experimental results.

1.3.2 Pressures at the wall

Distribution of pressures at the wall in the separated zone was measured (fig. 11) for different values of the relative length of emergence X/D of the tip.

Results presented in a typical case, $M_0 = 3.04$, $\theta = 45^\circ$, give the evolution of p/p_{i0} as a function of parameter x/X , which defines in a projection on the axis the position of the point of measurement relative to the theoretical reattachment point. /10

These results are conveniently grouped on a single curve, showing that in the flows studied the reattachment obeys a law of similitude.

The evolution of the pressure behind the base presents the following characteristics. A pressure plateau extending over 30 percent of the length of

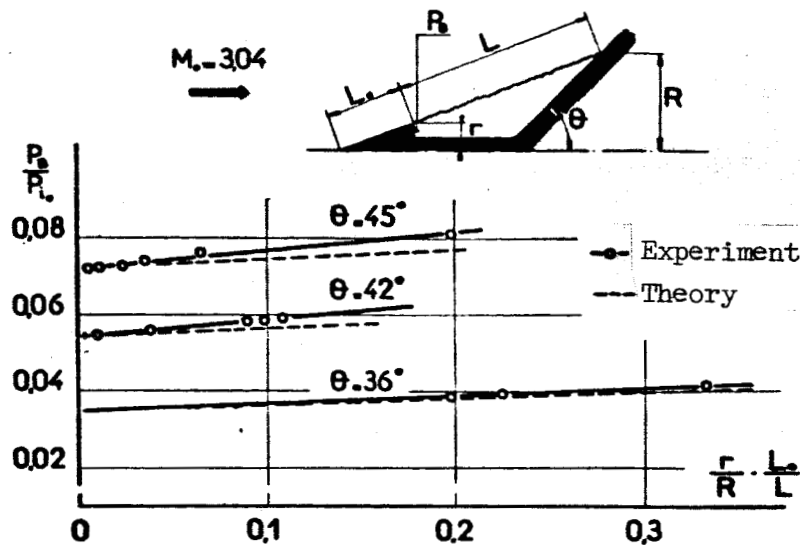


Figure 8. Influence of initial turbulent boundary layer.

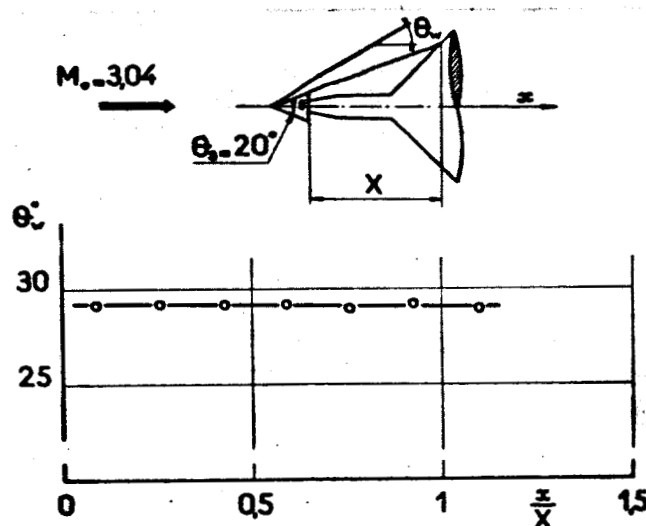


Figure 9. Conicity of external flow.

separation is followed by a rapid decrease in the vicinity of the recompression zone. This variation reaches 15 percent of the initial value. Such behavior is characteristic of a turbulent separation and shows the presence of a strong countercurrent. It will be noted, however, that its magnitude is particularly substantial for a conical separation.

The recompression which the flow subsequently undergoes is effected in two stages in the case under consideration. First, an abrupt variation of the

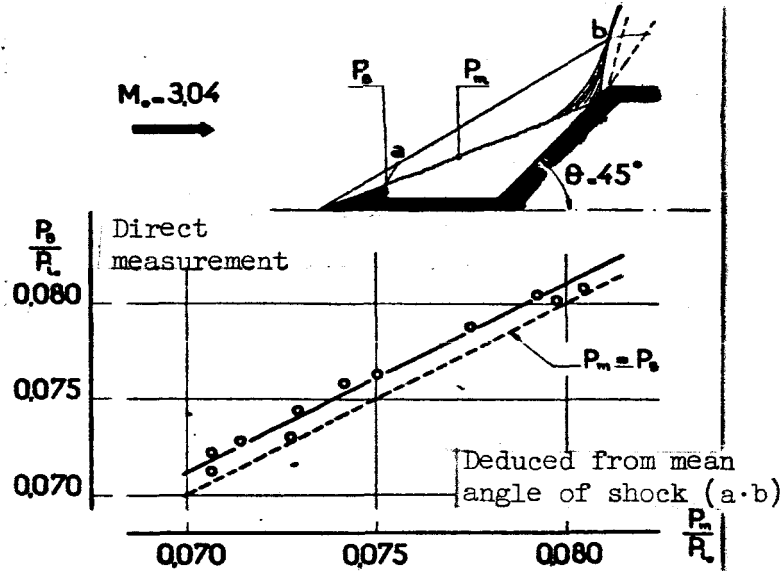


Figure 10. Comparison between base pressure p_B and pressure p_m at separation boundary.

pressure up to the theoretical reattachment point is recorded ($x/X = 1$). Beyond, the gradient d_p/d_x levels off, and the curve undergoes an inflection before reaching a maximum value close to that which would be provided by the isentropic recompression of a flow M_1 subjected to the deviation imposed by the wall of the cone. Then p decreases rapidly and tends toward the value corresponding to a conical flow of angle θ .

1.3.3 Influence of downstream limit conditions on the reattachment

The preceding curve has shown that an appreciable pressure drop follows the maximum pressure recorded at the wall; it might be asked whether this pressure drop substantially affects conditions of reattachment. For this reason, we attempted to determine the abscissa behind which any perturbation has no effect on the separation pressure.

The perturbation technique presented in figure 12 was developed for /11 this purpose.

After the base curve defining the recompression law has been carefully determined, an adjustable isobaric separation whose pressure is equal to the local value measured at the point considered in the absence of perturbation is induced at a variable abscissa X_p behind the origin of the recompression.

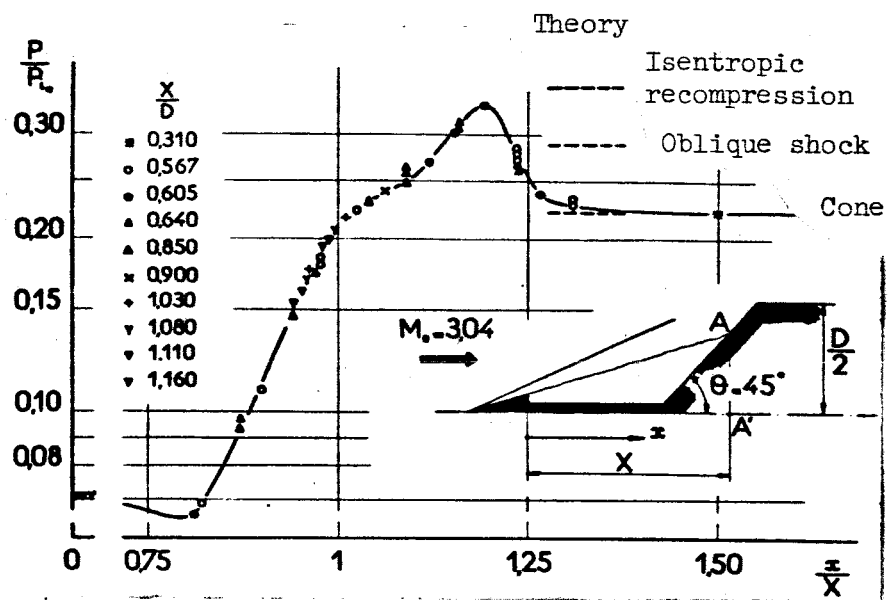


Figure 11. Distribution of pressures at wall.

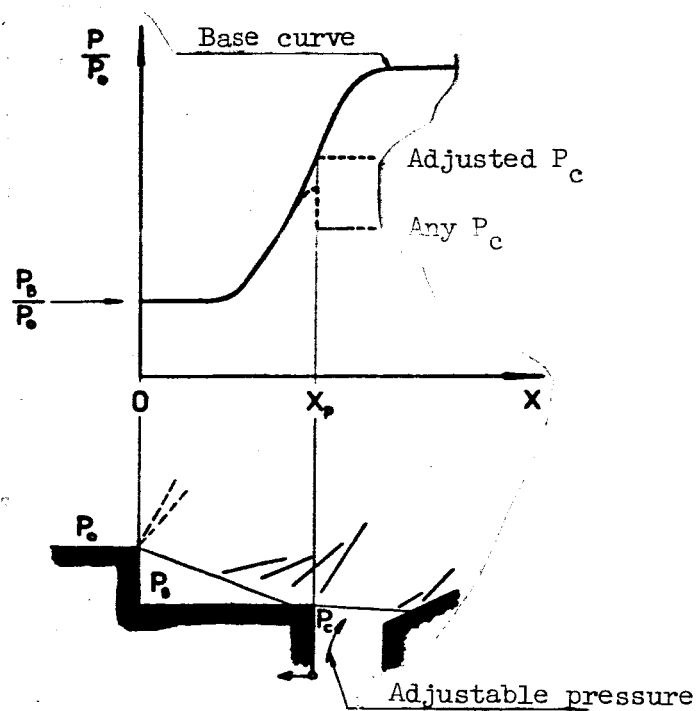


Figure 12. Perturbation method. Adjustment of its intensity.

Under these conditions there exists a value X_K such that if $X_p > X_K$, the part of the pressure curve located in front of X_p does not undergo any modification. On the other hand, if $X_p < X_K$, this curve is totally perturbed. Point K of abscissa X_K acts as a critical point; the reattachment phenomenon is therefore entirely determined by the evolution of the pressures and the shape of the wall in front of this point.

This method was used to define the critical point of the configuration studied earlier ($M_0 = 3.04$, $\theta = 45^\circ$).

The experimental position of K is located in this particular case at the intersection of the line of the isobaric jet and of the wall (fig. 13).

This experiment shows that:

- (a) the conditions of reattachment are valid for any downstream wall tangent at point K to the conical wall studied, which imparts some degree of generality to the results of these experiments, and

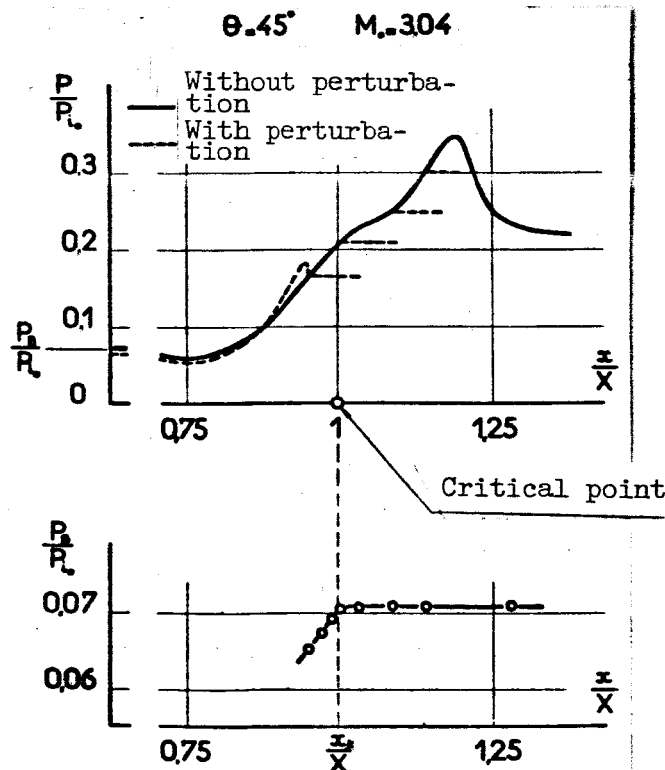


Figure 13. Conical separation. Definition of critical point.

- (b) the total pressure jump effectively observed in the course of a reattachment experiment cannot be considered as a characteristic parameter of the reattachment phenomenon.

1.3.4 Angular criterion of conical reattachment

These considerations lead us to present the results obtained during these tests in the form of a diagram $\psi = \psi(M_1)$, shown in figure 14.

ψ represents the angle of the isobaric jet line and of the wall at the critical point. /12

This parameter is an intrinsic, known quantity of the reattachment phenomenon.

The application of the Prandtl-Meyer rule to the deviation ψ makes it possible to present this same criterion in figure 15 in the more familiar form of a pressure ratio related to this deviation.

In each case, these results are compared with the Chapman-Korst escape criterion.

The very substantial deviations observed show the mismatching of this criterion with the type flow just analyzed.

2. Attempt at Generalization

To test the generality of the law of reattachment deduced from the study of conical separations, we performed reattachment tests on models substantially different from the preceding model.

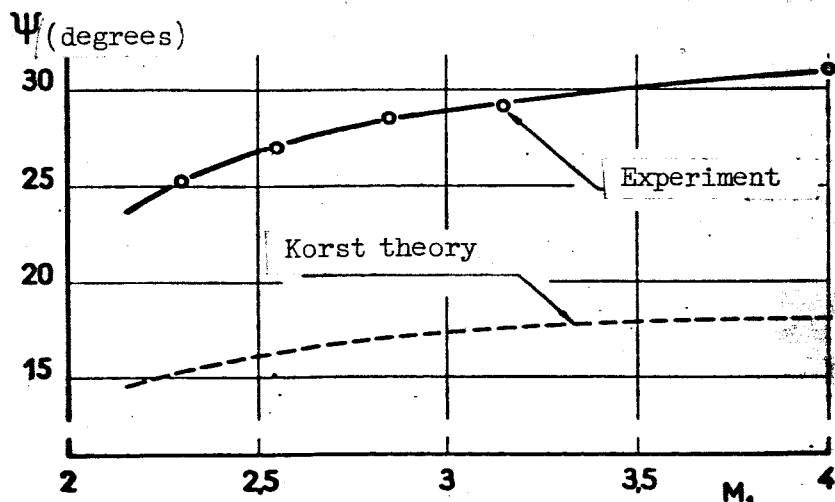


Figure 14. Angular criterion of conical turbulent reattachment.

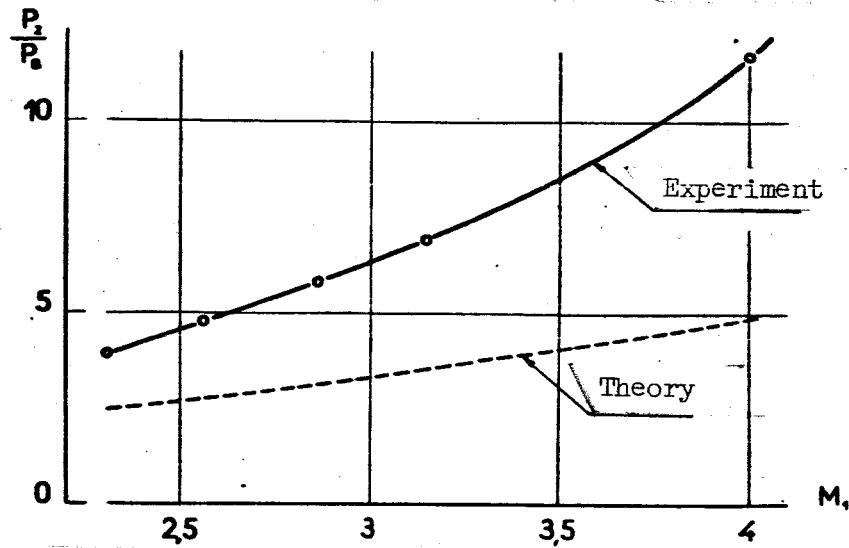


Figure 15. Pressures of conical turbulent reattachment.

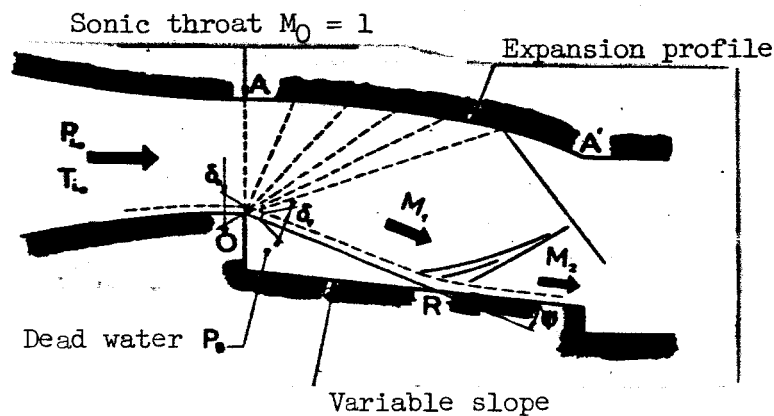


Figure 16. Plane flow arrangement.

The first arrangement, which was retained (plane stream, figure 16) installed in a wind tunnel of small dimensions, is characterized by the following features.

A wall breakoff located at the sonic throat of a nozzle marks the origin O of the separation; the shape of the opposite wall has been matched to represent a stream line of a Prandtl-Meyer pressure drop centered rigorously at O .

In this setup the level of the pressure drop at O is fixed by inclination of the downstream platform, and the jet line is rectilinear. The boundary layer at O , laminated by the pressure drop in the convergent channel, is extremely weak on the nozzle profile as well as on the lateral walls.

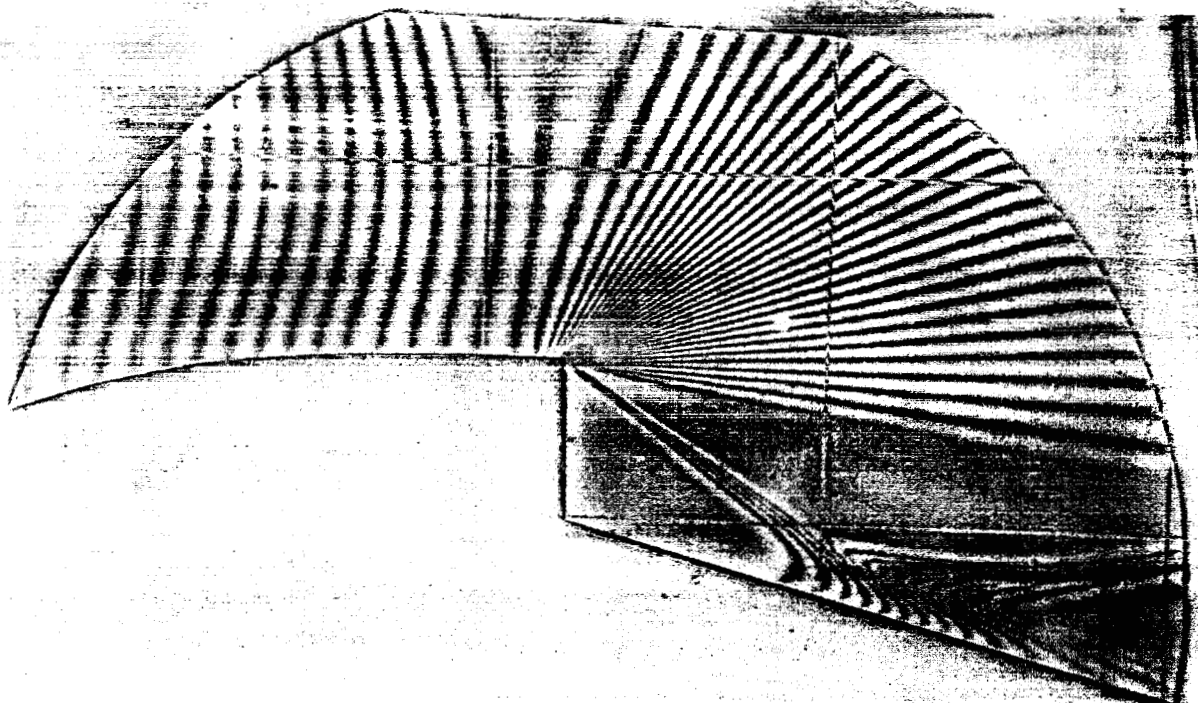


Figure 17. Interferogram of flow.

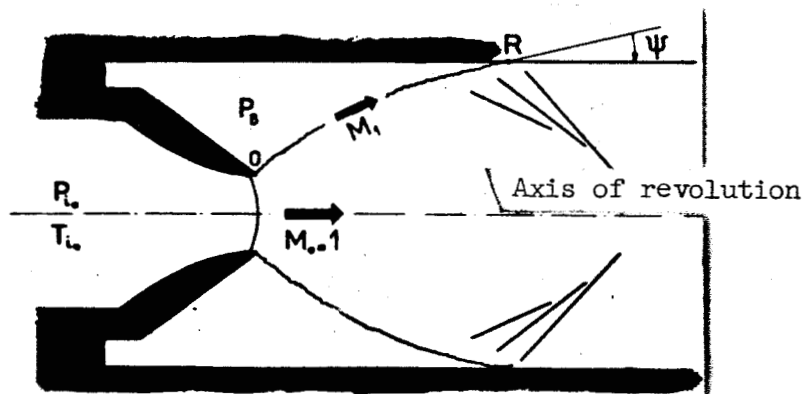


Figure 18. Flow-of-revolution arrangement.

This arrangement is mounted in the field of a Mach Zehnder interferometer which permits observation of this phenomenon and measurement of the specific masses, particularly in the region of reattachment (fig. 17). Results of interferometric measurements will be treated in a later publication; only ¹³ pressure measurements will be considered here. A second model (stream of revolution, fig. 18) has permitted study of the reattachment of a jet originating

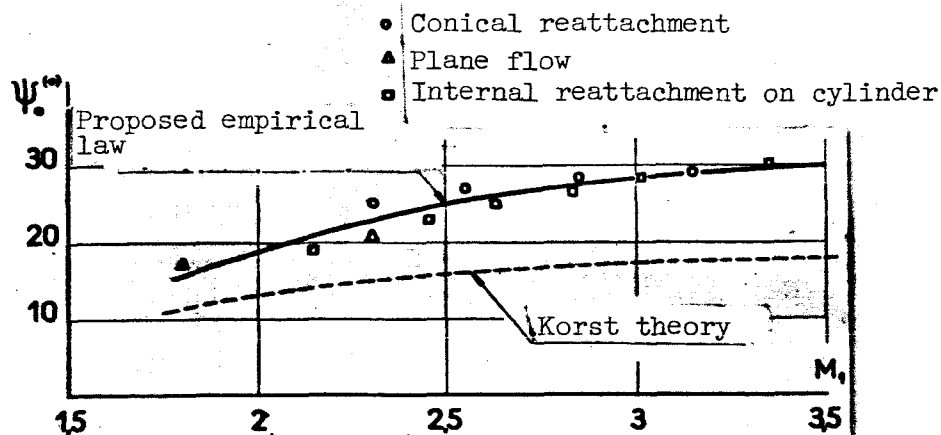


Figure 19. Angular criterion turbulent reattachment. Negligible initial boundary layer.

from a sonic nozzle on a cylindrical wall under similar conditions. The values $\psi(M_1)$ collected in figure 19 follow directly from the measurement of pressures in plane and conical flows. In the case of reattachment on the cylindrical wall, a perfect-gas calculation of the isobaric jet line for each measured base pressure gave $\psi(M_1)$.

Generally, all points thus obtained are located substantially above Korst's theoretical curve.

It is sufficient to recall that experiments cited as proof of the Korst criterion did not involve any correction for the boundary layer effect in order to explain the reasons for this discrepancy.

Thus, a curve deduced from the Korst criterion by introduction of a correction $C_q = 0.005$ according to formula 3 gives all these results reasonable approximation.

Although the experimental points obtained under varied conditions do not fall on a single curve, the proposed curve leaves only those discrepancies which amount to less than the effect of an error of 0.001 on the parameter δ^{**}/L .

Conclusion

A series of reattachment experiments performed under varied conditions, in the course of which we corrected or eliminated as best we could the numerous influencing factors involved in this phenomenon, permitted us to establish a new angular criterion of reattachment.

Although the universality of this criterion has not been proven, it is in our opinion and from the standpoint of applications a real process with respect to the reattachment laws heretofore employed.

It is deduced from the Korst criterion by assuming that the latter is valid for a flow which would involve a blowoff or boundary layer effect $C_q = 0.005$.

For further progress, it appears indispensable to carry out a more detailed study of the reattachment zone.

In this regard, we have already used a perturbation method to prove the existence of a critical point in the vicinity of the reattachment point.

Application of interferometric methods permits us to hope to contribute to the study of this important problem in the near future.

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